RADIOACTIVE WELL LOGGING WITH A
SCINTILLATION COUNTER

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with a
Scintillation Counter"

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Abstract

A coincidence scintillation counter, using a terphenyl crystal phosphor and 931A photomultiplier tubes, was constructed to be used as the detecting instrument in radioactivity well logging. It was hoped that it would prove at least as sensitive as the ionization chamber detector now commonly used. If this hope could be realized, its shorter sensitive length would provide a more precise location of strata.

The investigation showed, however, that this instrument has not a high enough sensitivity for gamma-ray well logging. The efficiency could possibly be improved by the use of another crystal and tube combination. Due to the crystal phosphor used, the efficiency of the counter drops off at high temperatures, so that at 60°C the response to cobalt 60 radiation is only 1/6 of that at 5°C. Since the temperature encountered in a borehole may be as high as 150°C it would be necessary to use a crystal which is not temperature dependent, or to provide a means of temperature control.

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1. Introduction

(a) Radioactivity Well Logging

In the production of oil from a well it is desirable to have as much information about the sub-surface strata as is economically possible. If it were possible to obtain an accurate driller's log or economically sound to take cores at all depths, the need for further data would be much decreased. But such is not the case. Driller's logs are inaccurate in that there is a time lag between the moment the bit cuts into a stratum and the time the cuttings are received at the surface. Besides this, it is not always easy to interpret the cuttings with certainty. Coring is an expensive and time consuming procedure. Even if cores could be obtained cheaply, it is often not possible to obtain all the cores in their proper relative position. In certain types of rock the cores may be disintegrated by the drilling fluid, and cannot be recovered intact.

The information provided by the driller's log, or by occasional cores, must be supplemented by other methods, especially for accurate location of the different strata. Electrical logging and radioactivity logging are the two methods in most general use. The electrical method depends on a measurement of the resistivity of the surrounding rock, and the spontaneous potential developed in the borehole. It cannot be done after the casing has been set in the hole, or if highly conductive liquids are present. It is in these cases in particular that radioactivity logging has proved its value.

A case of particular importance is where a well has been drilled through a gas or oil sand, to a lower producing zone. When the production from the lower zone has dropped off, it is desirable to determine the depth of the cased off potential zone, and perforate the casing at this point to restore production. By means of a radioactivity log, the zone can usually be accurately located.

Radioactivity logging is best dealt with under two separate headings: Gamma-ray Logging, and Induced, or Neutron Logging. In the former process, a log is taken of the naturally occurring radioactivity at each depth. Since different types of rock differ in a known manner in their radioactive content, it is possible to identify the strata, within limits, from the gamma-ray log. Figure 1, from a paper by Russell (1), shows the relative gamma-ray intensities of several sedimentary rocks.

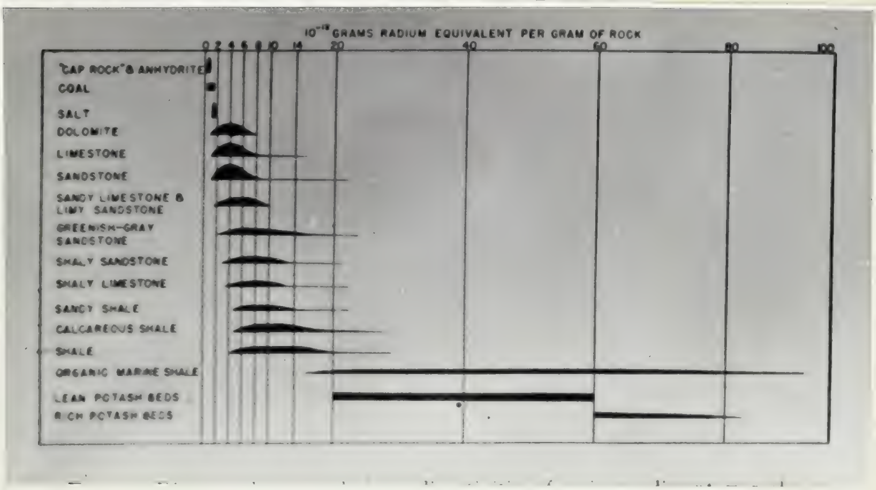


Figure 1. Radioactivity of Sediments

The vertical width of line increases with frequency of occurrence, and the intensity of radiation increases to the right. A general rule is that the darker the rock, the higher the radioactivity. For example shales are high where limestones and dolomites are low.

As to the source of the radioactivity, Tiratsoo (2) claims that most of it is due to the K^{40} isotope. This isotope makes up about 0.011% of naturally occuring potassium, which is the seventh most abundant element, and makes up 2.40% of the lithosphere. Russell (3)(4), on the other hand, states that the contribution of the Uranium and Thorium series is important. Russell (4) also gives quite a comprehensive study on the Relation of Radioactivity, Organic Content, and Sedimentation.

The gamma-ray intensity does not indicate the porosity, or the fluid content of the rock. The neutron curve, used in conjunction with the gamma-ray curve, supplies this information. When neutrons are allowed to bombard the strata surrounding a borehole, secondary gamma radiation is produced, which is dependent largely upon the quantity of hydrogen present. Hydrogen, whether in oil, gas, or water, has the effect of slowing down the neutrons without appreciable gamma radiation. Neutron logs show all hydrogen bearing strata and shale zones as lows. By comparison with the gamma curve, in which shales are high and limestones, sandstones and dolomites are low, it is possible to determine where possible producing zones are located, although it is not usually possible to distinguish between

oil, gas and water. Figure 2 is a graphical representation of interpretation of the combined logs as set forth by the Lane-Wells Company (3).

Other types of induced radioactivity logging has been suggested, but as far as is known no definite data have been obtained. One method mentioned is to bombard the borehole with gamma rays, and measure the resulting scattered radiation.

At present the Lane-Wells Company is the major organization engaged in making radioactivity logs in the field. To obtain the gamma curve, the detecting instrument used is an ionization chamber filled with freon at a high pressure, so as to present a large stopping mass to the gamma radiation. The length of the chamber is three feet. With this relatively long detecting unit, the boundary between two different layers of rock appears on the record as a gradual transition, instead of a sharp break. However, the length is required in order to intercept enough radiation to give an easily measurable result.

Since the neutron-induced radiation is of higher average intensity, a shorter chamber - only one foot long - can be used. A radium-beryllium neutron source is placed in the subsurface instrument with appropriate shielding to keep the gamma radiation of the radium from activating the ionization chamber. The secondary gamma radiation received is of sufficient intensity that the natural gamma radiation is usually negligible.

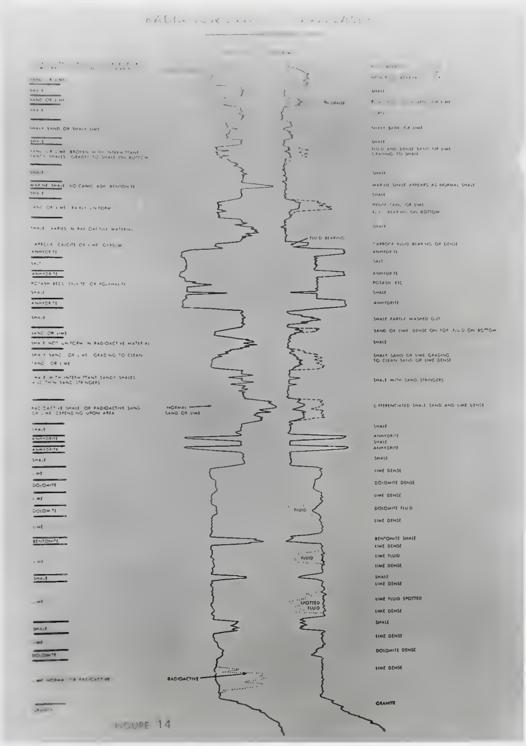


Figure 2. Typical Radioactivity Log
Interpretation

With both detecting instruments the ionization current is amplified and transmitted to the surface. Here it is plotted on a recording meter whose paper drive mechanism is synchronized with the depth of the detecting instrument by means of a pair of selsyn motors.

(b) Scintillation Counters

(i) Scintillation Counter as the Detecting Instrument

The familiar Geiger-Muller counter has not proved practical for radioactivity logging, on account of its low efficiency for gamma rays. However it has been stated that a scintillation counter is up to 60% efficient for gamma ray quanta, as compared with 0.5% for geiger tubes. With this high efficiency it appears that a scintillation counter would be practical as a detector in radioactivity logging.

The shorter detecting unit - about one inch - of a scintillation counter would make it possible to locate the breaks in a log much more precisely. Should a scintillation counter prove more sensitive than the present ionization chamber, it would give a better identification of all strata and also permit a higher logging speed within the same limits of statistical fluctuation that now exist.

(ii) Principles of Scintillation Counter

Many crystals and liquids fluoresce when they are bombarded by high-speed particles, or exposed to short-wave-length radiation. Such materials are known as "phosphors". If the energy of the particles or photons is great enough, the fluorescence caused by a single particle may be enough to be visible, as in Rutherford's original "scintillation" method of counting the alpha particles bombarding a fluorescent screen. If a large mass of phosphor is exposed to gamma rays, many of the gamma-ray quanta will excite scintillations when they are absorbed somewhere in the phosphor. Under proper conditions the light of a single scintillation can be detected electrically with a photomultiplier tube. Since the phosphors employed are relatively dense, they stop most of the gamma-ray quanta. Hence a scintillation counter can have a high efficiency as compared with a gas-filled Geiger tube.

In a photomultiplier tube the light falls on a photosensitive cathode, and ejects electrons. The electrons are accelerated by an applied potential towards a "dynode" plate, which they strike with sufficient energy to cause secondary emission. The secondary electrons are accelerated towards a second dynode, and so on. The tube contains from 9 to 11 of these dynode stages so that finally about 10^6 electrons reach the collecting anode for each primary photo electron released from the cathode. When used with a scintillation phosphor, each scintillation produces a pulse in the photomultiplier circuit. This pulse can be amplified, and recorded on any conventional counting device.

A difficulty encountered with the scintillation counter is the dark current noise in the photomultiplier tube. The electrode surfaces, having a low work function, as is necessary for good sensitivity to light and electron bombardment, release a few thermoelectrons even when no light is incident upon them. Only dark current pulses due to emission from the cathode are fully amplified, and affect the counting circuit. The number of dark current pulses varies from tube to tube, but is somewhere in the region of 10,000 to 100,000 counts per second (6).

(iii) Available Materials for Scintillation Counters

(1) Photomultiplier Tubes

There are a number of photomultiplier tubes on the market. Table I (7) is a table of the more frequently used tubes with their main characteristics. The main points to be considered in the choice of a photomultiplier tube are its spectral response, dark current noise, and amplification factor. A point to be considered is that all tubes of one type have not necessarily identical characteristics. Due to the sensitive nature of the tubes, it would be very difficult and costly to insure that all were identical.

(2) Phosphors

Table II (8,9,10) is a table of the more common crystal phosphors available with their main characteristics. Table III (11) is a table of the more recent liquid phosphors with the one

Table I
Characteristics of commercial photomultipliers

Tube Type		RCA 931A	RCA 1P21	RCA 1P22	RCA 1P28	RCA 5819	EMI 4588	EMI 5060	EMI 5311
Photo-cathode	type	internal	internal	internal	internal	tube end	internal	tube end	tube end
	area	1.9 cm^2	1.9 cm^2	1.9 cm^2	1.9 cm^2	11 cm^2	20 cm^2	0.7 cm^2	5 cm^2
	spectral class	S-4	S-4	S-8	S-5	S-9	like S-4	like S-9	like S-
	peak response	4000A°	4000 A°	4200 A°	3400 A°	4800 A°	—	—	—
	longwave cutoff	7000A°	7000 A°	8000A°	7000A°	7000 A°	—	—	—
	sensitivity	10 ua/l	40 ua/l	3 ua/l	15 ua/l	40 ua/l	40 ua/l	20 ua/l	20 ua/l
Gain	number of stages	9	9	9	9	10	9	11	11
	volts per stage	100	100	100	100	90	150	160	160
	average gain	10^6	$2x10^6$	2×10^5	$2x10^5$	6×10^5	$\sim 10^6$	10^7	10^7
Capacity	coll* to last dynode	4 uuf	4 uuf	4 uuf	4 uuf	5 uuf	—	—	—
	coll* to total structure	6.5 uuf	6.5 uuf	6.5 uuf	6.5 uuf	8 uuf	—	8 uuf	—
Voltage	overall (maximum)	1250	1250	1250	1250	1250	1500	—	—
	coll* to last dynode	250	250	250	250	150	150	180	180
Current	coll* (maximum, average)	1.0 ma	.1 ma	1.0 ma	2.5 ma	.75 ma	1 ma	1 ma	1 ma
	dark current	.25 ua	<.1 ua	.25 ua	—	.05 ua	.03 ua	.01 ua	.1 ua

* Collective

Table II

General Properties of Luminescent Materials

Phosphor	Emission Spectrum in Angstroms		Decay Constant in 10^{-8} sec.	Density in gm/cm^3	Relative Light Yield for Betas	Energy Yield for Alphas	Energy Yield for Gammas *
Anthracene[1]	4440 4120 4720	Strong	3.0	1.25	1.0	-	-
Naphthalene[2]	3450 3650		6.0	1.15	0.25	0.003	0.05
Phenanthrene[3]	4100 4300		0.8	1.07	0.3	0.006	0.11
Zinc Sulphide-Silver Activated[4]	4500		1000	4.10	2.0	0.28	0.14
Sodium Iodide-Thallium Activated[5]	4100		25	3.67	2.0	-	0.05
Calcium Tungstate[6]	4300		30	6.06	1.0	0.017	0.08
Cadmium Tungstate[7]	5300		100	7.[illegible]	[illegible]	-	-
Stilbene[8]	4080 4200	Strong	0.6	1.16	0.4	-	-
Terphenyl[9]	3900 4050 4300		1.2	1.23	0.6	-	-

* Fraction of incident energy converted into ~~//~~ luminescent photons.
1 Good crystals hard to grow.
2 Good crystals easily gorwn: sublimes.
3 Difficult to obtain clear crystals.
4 Only powder or small crystals available.
5 Excellent crystals; hygroscopic.
6 Good small crystals readily obtained.
7 Good small crystals readily obtained.
8 Excellent crystals readily obtained.
9 Large shock resistant crystals readily obtained.

Table III

Liquid Phosphors

Liquid or Solution	Efficiency*
Benzene	0.07
Benzene @ 70°C	0.07
Ether	0.07
m-Xylene	0.08
Naphthalene (40g) in benzene (100 cc)	0.15
Naphthalene (35g)+anthracene (.35g) in benzene (90 cc)	0.36
Terphenyl (2g) in benzene (100 cc) at 60°C	0.84
Terphenyl (0.5g) in m-Xylene (100 cc)	0.80
Liquid dibenzyl at 60°C	0.4
Naphthalene Crystal	0.87

* A coincidence circuit was used to determine the efficiencies. If A Compton electrons are formed in the solution each second, each photomultiplier tube counts $n = xA$ times per second, where $x < 1$. The number of coincidences per second is given by $c = x^2A$. Thus the ratio $\frac{c}{n} = x$ is a measure of the "efficiency".

Efficiencies are at room temperature unless otherwise noted.

characteristic studied. Important factors to take into account when selecting a phosphor are the density, the spectrum emitted, decay constant, and the efficiency for various radiations. Although phosphors have been used for many years, the intensive study of their characteristics is a fairly recent development, and there is still no standard method of expressing the efficiencies. The mass of recent data is inclined to be difficult to interpret. Whereas one author gives the efficiency as the quantity of light produced within the phosphor per unit energy absorbed, a second will state that the efficiency is the quantity of light transmitted from the phosphor per unit energy of radiation absorbed. These differ appreciably on account of the light transmission characteristics of the material. Until the studies become more advanced it is doubtful if standardization will be introduced.

(iv) <u>Construction Principles of the Scintillation Detecting Unit</u>

It is desirable that as much as possible of the light produced by the phosphor be transmitted to the photosensitive cathode of the photomultiplier tube, and hence it is necessary to obtain good optical contact between the phosphor and the tube. Liquid phosphors automatically provide very good optical contact with a tube which is immersed in the liquid. In the case of crystal phosphors, it is usually necessary to shape the crystal to conform to the tube, and cement it to the glass surface.

The dark current noise produced by a photomultiplier tube is a hindrance in determining low counting rates accurately. To reduce the dark current to a minimum, the tube may be cooled to liquid air temperature. Another method of eliminating the dark current effect is to employ a coincidence circuit with two photomultipliers viewing the same phosphor. The only background noise recorded is then the small number of accidental coincidences between thermoelectric pulses in the two tubes.

2. Theoretical Considerations

(a) Absorption

Radioactivity of rocks has been measured by several investigators (2) (3) and the results stated in equivalent grams of radium per gram of rock, but no data are available on the intensity of radiation to be expected in a borehole in terms of generally accepted radiation units, such as roentgen units. The principal factor determining the intensity of radiation in a continuous medium are:

(1) concentration of the active material and energy of the radiation;

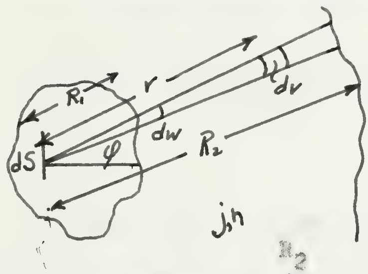
(2) the absorption coefficient of both the emitting medium and the detecting medium, and their respective geometry;

(3) energy transfer by Compton scattering, pair production and photoelectric emission.

Various authors have discussed the effect of self-absorption in radioactive sources. Radiation from distributed sources of linear, cylindrical, and spherical geometries, has been calculated for positions of the detector outside the source, but no method has been published for an extensive distributed source, with the detector inside the source. A method is here proposed, but calculations are limited to simple geometries. Other types of geometry require extensive mathematical treatments which are not attempted in this thesis.

Case (i)

Consider a uniformly distributed source emitting j quanta per cc per second, with an absorption coefficient n cm^{-1}. Also consider a non-absorbing cavity within the source, as is shown in the accompanying sketch.



If I_w is the flux received at dS per unit solid angle, then $I_w dW$ is the flux received from the element of solid angle dW, so that

$$I_w dw = \int_{r=R_1}^{R_2} \frac{j}{4\pi r^2} e^{-n(r-R_1)} dv \quad \ldots\ldots\ldots\ldots\ldots (1)$$

But $dv = r^2 d\,w\,d\,r$, so

$$I_w = \int_{R_1}^{R_2} \frac{j}{4\pi} e^{-n(r-R_1)} dr$$

$$= \frac{j}{4\pi n} \left(1 - e^{-n(R_2-R_1)}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

If $nR_2 \gg 1$, and $R_2 \gg R_1$, as is certainly the case in a borehole, the exponential term can be neglected, and

$$I_w = j/4\pi n \text{ quanta/cm}^2\text{/sec/steradian}, \quad \ldots\ldots\ldots\ldots\ldots (3)$$

independent of E_1. In this case the total radiation traversing dS from the right will be,

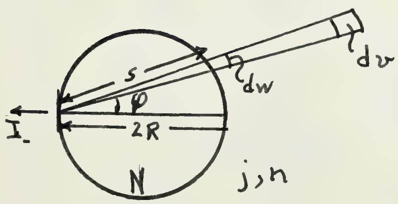
$$I_+ = \int_{\text{hemisphere}} I_w \, dw. \quad \text{But } dw = \sin\varphi \, d\theta d\varphi$$

$$\text{and } I_+ = 4 \int_0^{\pi/2}\int_0^{\pi/2} I_w \sin\varphi \, d\theta d\varphi$$

$$= j/2n \text{ quanta/cm}^2\text{/sec} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

<u>Case (ii)</u>

Consider now a uniform sphere of radius R cm and absorption coefficient N cm^{-1}, in an infinite distributed source with the same parameters j and n as above. The flux inward for a point on the surface of the sphere will be the same as the I_+ obtained in equation (4). Now, if the outward flux is determined, it will be possible to determine the number of quanta absorbed by the sphere.



From the sketch shown,

$$I_- = \int_{\text{hemisphere}} I_w e^{-Ns} \, dw \quad \ldots (5)$$

If we let $u = \mathrm{Cos}\,\varphi$, then $dw = -du\,d\theta$, and $s = 2Ru$. Therefore,

$$I_- = 4 \int_0^{\pi/2} \int_0^1 I_w e^{-2NRu} \, d\,u\,d\theta,$$

which reduces to

$$I_- = \frac{1}{4nNR} \left[1 - e^{-2NR} \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

If now we take the ratio $(I_+ - I_-)/I_+$ we obtain the fraction of incident energy that is absorbed. It should be noted that

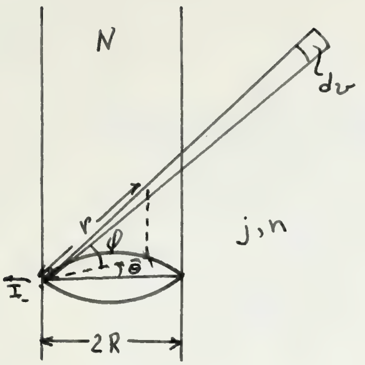
$$(I_+ - I_-)/I_+ = f_1\,(NR) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and is independent of the parameters of the source.

Case (iii)

If now the same quantities, for an infinitely long cylinder, with parameters R and N, can be obtained, the result will give an indication of the count that could be obtained with an absorbing detecting instrument in the borehole. I_+ in this case will be the same as for the sphere, as it is independent of shape of the cavity, but I_- will be

$$I_- = \int_{\text{hemisphere}} I_w e^{-Nr} \, dw \ldots\ldots\ldots\ldots\ldots\ldots (8)$$



where the values are as shown in the sketch, and

$r = 2R\cos\theta/\cos\varphi$. With the particular angles shown,

$dw = \cos\varphi \; d\theta d\varphi$ so that

$$I_- = 4\int_0^{\pi/2}\int_0^{\pi/2} I_w \exp\left(-2NR\cos\theta/\cos\varphi\right)\cos\varphi \; d\theta d\varphi \quad ..(9)$$

Again, the absorption is a function of NR only, say

$$(I_+ - I_-)/I_+ = f_2\,(NR) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

The integral in (9) cannot be evaluated in simple terms. However, the above work does show a method of determining the intensity of radiation in a borehole, and $f_2(x)$ could, if necessary, be evaluated numerically for a series of values of x.

Case (iii) does not accurately represent the actual condition in the borehole. Firstly, there is the fact that a detecting instrument is not infinitely long, and secondly, absorption in the casing wall has not been considered. The effect of the casing wall is not great until the angle " φ " becomes large. Then, any radiation entering the detector must traverse a considerable thickness of metal.

(b) Statistical Fluctuations and Rate of Logging.

Russell (1) has stated that, as the sensitivity of the Lane-Wells ionization chamber is increased, the logging rate must be decreased, in order that statistical fluctuations will not hinder the interpretation of the log. The wording used is somewhat ambiguous, since the meaning of the word "sensitivity" is not defined. "Sensitivity", as Russell uses it, must mean the amplification applied to the ionization current fluctuations, since it would not be possible to change the pressure or volume of an ionization chamber at the bottom of a well by merely turning a dial at the surface. If this is the case, Russell's argument holds. He states that an averaging circuit with a 10 second time constant is used when logging speeds of 1500 feet an hour are employed. This averages the intensity of radiation over the thinnest strata likely to be encountered; about 4 feet. If the thickness of casing or cement surrounding the borehole is great, a very low intensity radiation will be observed, and it will be necessary to increase the sensitivity of the instrument in order to note the variations in intensity. In so doing, the statistical fluctuations are also amplified by a corresponding factor, and they render the log difficult to interpret. To overcome this, a longer time constant is used in the circuit, to smooth out the statistical fluctuations. Then, at the same rate of logging, the instrument would not stay opposite a thin layer of rock long enough to log it accurately, so it is necessary to decrease the logging speed.

On the other hand, if the real sensitivity of the detector could be increased, by increasing the fraction of incident radiation which is absorbed, the relative statistical fluctuation would be decreased. This would allow a decrease in the time constant of the recording circuit, and an increase in the logging speed. It is in this sense that the term "sensitivity" is used in this thesis.

3. Apparatus

(a) Detecting Unit

(i) Materials Employed

A liquid phosphor has obvious advantages, and in the first attempt to make a scintillation counter suitable for well-logging, a solution of terphenyl in xylene was chosen. According to Reynolds (12) this solution has a decay time of about 0.02 μ sec., and gives light which is well matched spectrally to either a 931A or a 1P21 photomultiplier tube. Difficulty was encountered, however, in obtaining reproducible results with this liquid, and it is believed that the purity of the solution was at fault. Since the tubes had to be immersed in the liquid, and the whole apparatus had to be portable, it was necessary to have the tubes sealed into a can containing the phosphor. Xylene is a strong solvent and attacks rubber and bakelite, so it was necessary to use an insoluble plastic paint made up of cellulose acetate dissolved in acetone for the sealing compound. The bakelite bases of the photomultipliers were covered with many coats of this paint.

When this arrangement was used, the response was very erratic. Usually after the solution had been sealed in for a time its ability to scintillate dropped off. It is thought that the liquid was able to get at some minute exposed parts

of the bakelite, since it was difficult to obtain a good contact between the bakelite and the plastic paint. Even when the solution was working at its best it gave only about 2/3 the response obtained with a 2 cc naphthalene crystal. The quantity of liquid phosphor within the range of both photocathodes was about 12 cc.

After the difficulties encountered with the liquid phosphor a terphenyl crystal, shaped to fit between two 931A tubes, was obtained. This crystal, with about 9 cc exposed to both photo-cathodes, produced a twenty fold increase in sensitivity over the small napthalene crystal.

At the time the instrument was constructed, there were 10 931A tubes on hand. Since it is possible to substitute 1P21s directly for 931As, a matched set of 1P21 tubes was ordered, and construction was begun with the less sensitive 931As. It was not possible to obtain the 1P21s while the research was in progress, so 931As were used throughout. Of the 931As available the two that were best matched were chosen. This was done by comparing both noise and signal pulses on a Lavoie Oscilloscope.

(ii) Construction

As mentioned above, in the first attempt, the tubes were sealed into a brass can containing the liquid phosphor. With the terphenyl crystal it was not necessary to make the unit leak-proof, but it was necessary to protect the photo-cathodes from the

least amount of extraneous light, and so a similar can was used. To obtain this, the tubes were inserted through rubber gaskets, shown cross-hatched in Figure 3, with another gasket under the cover of the can. The shape of the crystal, and its size relative to the photomultiplier tubes, are shown in Figure 4. Even with the rubber gaskets it was necessary to cover the can with a heavy dark cloth when the instrument was exposed to light.

(b) Circuits and Recording Unit.

The circuit for the preamplifier section was the same as that used by Coltman (6) except for a change in the size of the grid resistor. Figure 5 shows a complete circuit diagram of the instrument. Separate preamplifiers and pulse inverters were used for the two photomultiplier tubes. The preamplifiers were of the wide-band type since, if they are to pass pulses of short duration and short rise time they must be able to handle a wide range of frequencies. The potential dividers for the photomultiplier tubes provided equal voltage steps for the various dynode stages, although Mitchell (7) has suggested that a higher potential on the first stage and on the last few stages will produce a higher gain.

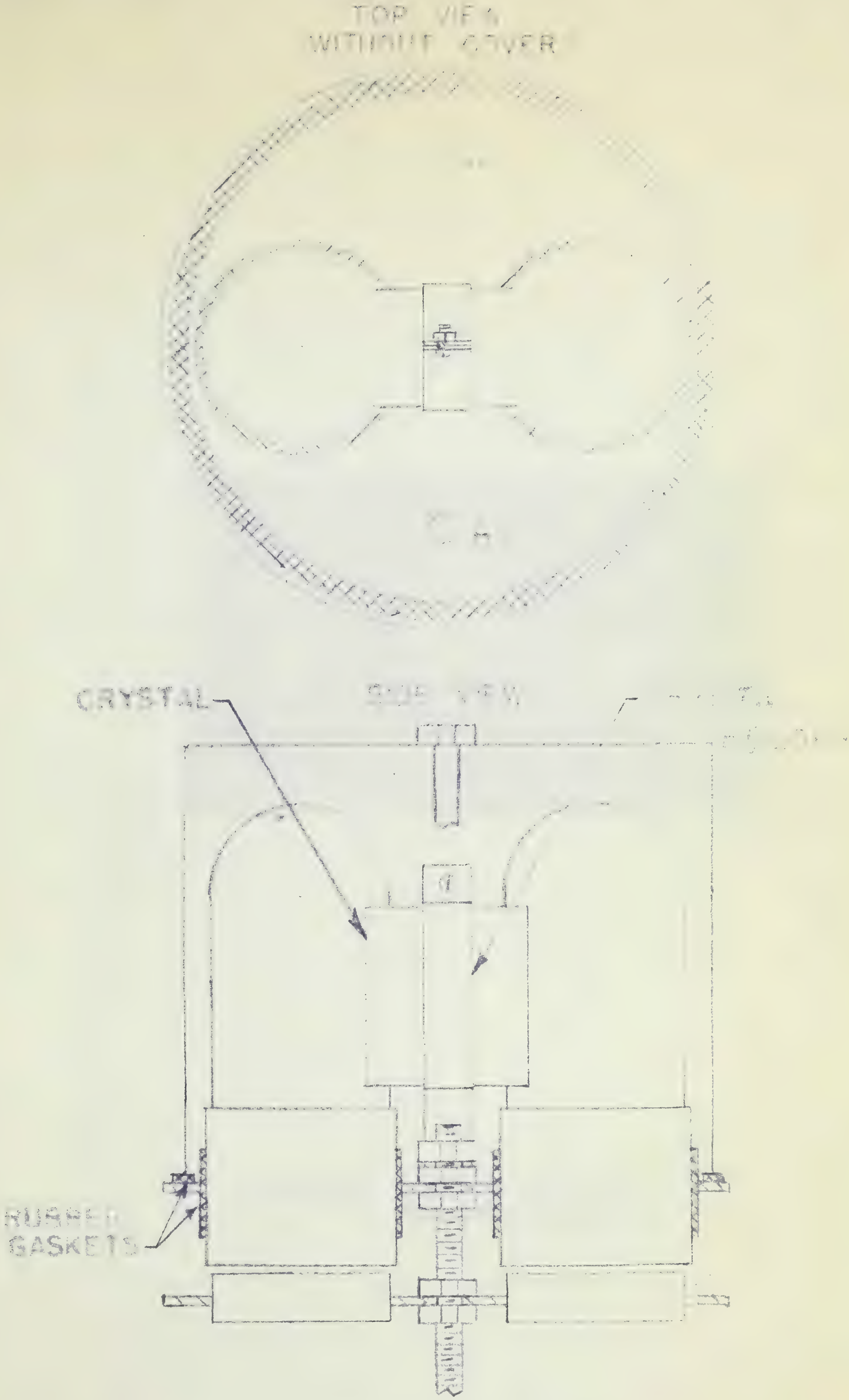


Figure 3. Photomultiplier Housing

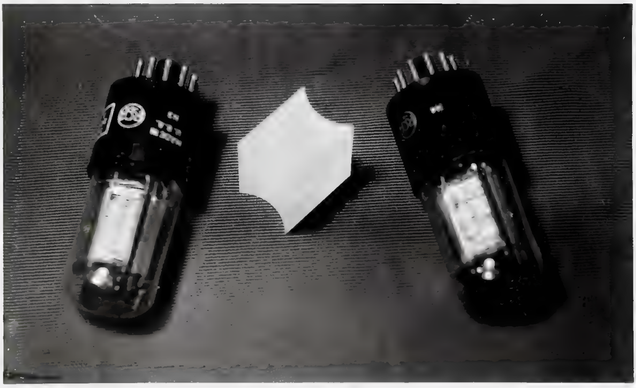
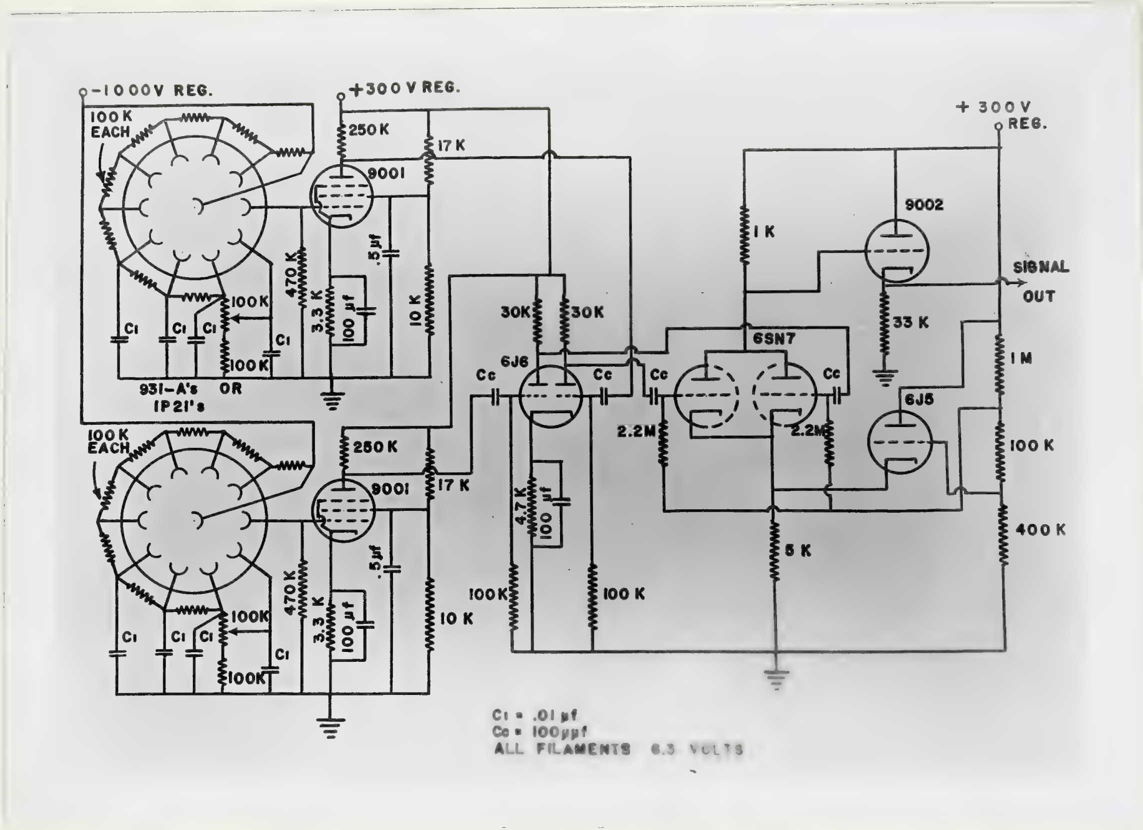


Figure 4. Terphenyl Crystal and
931A Photomultipliers



931A or 1P21	9001	6J6	6SN7 and 6J5	9002
Multipliers	Preamplifiers	Inverters	Coincidence	Cathode Follower

Figure 5. Circuit of Scintillation Counter

The 0.01 μf condensers (C_1 in Fig. 5) across the bleeder at each of the last four dynode stages of the photomultiplier tube were inserted to handle very large instantaneous currents during large signal pulses. A gain control is also provided at the last dynode stage, to permit lowering the amplification so as not to overload the 9001 pentode when large pulses occur.

The coincidence circuit used is one devised by Elmore and Sands (13), and requires negative pulses of 30 volts or more. The output pulse is of the order of 20 volts positive. Separate power supplies were used for the coincidence circuit and the amplifiers to guard against feedback from the coincidence circuit to the amplifiers.

A cathode follower is provided on the output to drive at low impedance the cable leading to the recording unit.

It was necessary to mount all the components shown in Figure 5, plus the crystal, in a cylindrical case which could be lowered into a borehole about 5 inches in diameter. As is shown in Figure 6, 4 brass discs, about 3 3/4" in diameter were mounted on a 1/4" steel rod running through their centers. The discs provided space to mount the eight vacuum tubes, and one large triple 100 μf condenser. The resistors were mounted on strips parallel to the center rod, to provide sufficient space for the remaining components.

Figure 6. Scintillation Counter
Detecting Instrument

The recording unit consisted of a discriminator and scaler incorporated in an Atomic Instrument Company Model 101A Scaler, and a D. C. amplifier and recording milliameter obtained from a Brush Strain Analyser. The scale of 8 output was connected to the D. C. amplifier of the Brush Recorder, giving a "pip" for each eight pulses. The recording pen was capable of a frequency of 100 c.p.s. so that an upper limit of about 60,000 c.p.m. was set by the recorder. It was originally hoped that the response to gamma radiation in the borehole would be high enough to place a R.C. averaging circuit between the scaler and the D. C. amplifier, thus converting the recorder into a counting rate meter.

A 9 wire shielded cable was used to conduct power to the detecting instrument, to conduct pulses to the surface, and to support the instrument. Only 7 of the 9 wires were required. The cable shield was strong enough to support the weight of the instrument and 100 feet of cable.

(c) Instrument Case

Pressure at the bottom of a borehole, filled with drilling mud, can be approximately 1000 p.s.i. per 1000 feet. This necessitates a very strong pressure tight outer casing. Since only about 60 feet of water would be encountered in the preliminary field trials, less strength was required. Nevertheless there was some difficulty

in obtaining a pressure tight case. In order that the instrument would not be too heavy for the cable, and so that not too many gamma rays would be absorbed in the case, an aluminum pipe was used. Its dimensions were 4.5" outside diameter by 27" long, with a 1/4" wall. Figure 7 is a cross-sectional view of the case. Note that the inner flange, to which the top cover is connected, has about 1/8 of an inch filed off on two opposite sides so that it can be placed inside the permanent 1/8 inch flange.

Figure 8 shows the detector with all associated equipment except the recorder.

(d) Adjustments

(i) Gain of Photomultipliers

Even though a matched pair of photomultiplier tubes was selected, it was necessary to make further adjustments so that both tubes had approximately the same noise background. This again was done with the aid of the Lavoie oscilloscope. In order to have maximum amplification the tube with the lower noise background was set at full gain. Then the gain on the second tube was reduced until its noise pulses appeared the same as the noise pulses of the first tube. At this setting, both tubes gave about the same response to a signal produced by irradiating the phosphor with gamma rays.

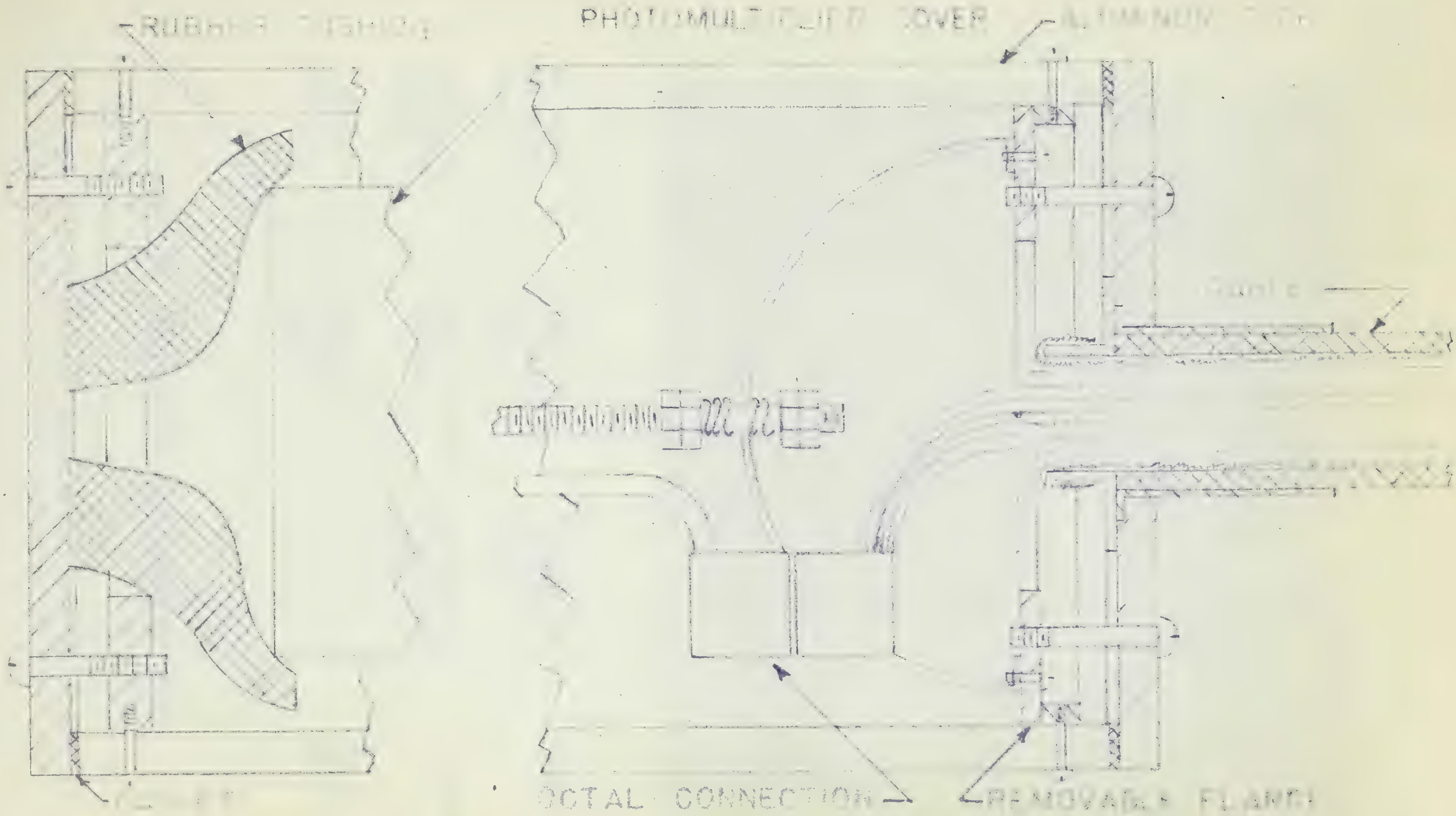
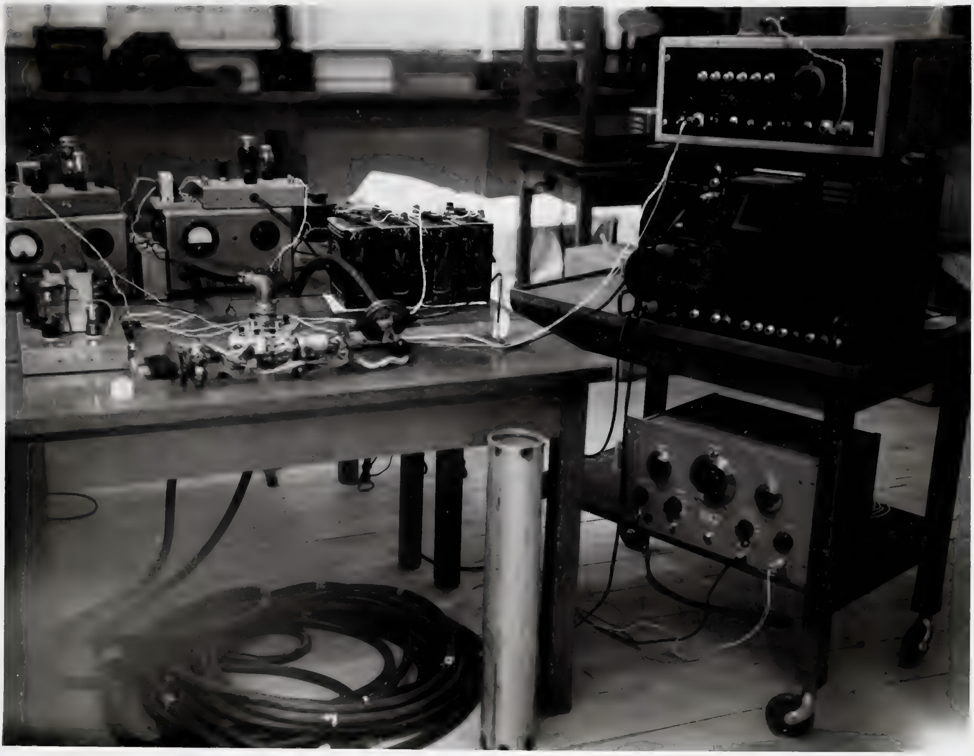


Figure 7. Cross Section of Instrument Case



300 Volt Regulated Supply	300 Volt Regulated Supply	6 Volt Filament Supply	Scaler
-1000 Volt Regulated Supply	Scintillation Counter	Aluminum Instrument Case	Oscilloscope
Terphenyl Crystal	100 Foot 9 Wire Cable		Pulse Generator

Figure 8. Detector and Associated Equipment

(ii) Discriminator Setting

Owing to the nature of the coincidence circuit, small pulses were obtained at the output even when a coincidence had not occured. This was observed by turning the gain on one photomultiplier as low as possible so that the tube was no longer in operation. Signal and noise pulses from the second tube were observed as 1 1/2 to 2 volt pulses at the output. To eliminate these the discriminator was set at +3 volts for all subsequent tests. This setting did discriminate against some partial signal coincidences, but would also block partial noise coincidences.

(iii) Pulse Length and Resolving Time

The output at the anode of a photomultiplier is a charge which produces a voltage upon the anode capacitor. The anode capacitor is made up of the anode capacitance of the photomultiplier tube, the grid capacitance of the preamplifier tube, and the stray capacitance due to sockets and wiring. If the grid lead is kept to a minimum length an anode capacitance of about 11 $\mu\mu f$ is possible. Theoretically, the limiting factor in pulse height is the size of this capacitance. The grid resistor serves only as a bleeder for the capacitor. The time constant of this circuit governs the length of the pulse, although the decay constant of the phosphor sets a lower limit.

However, if the R. C. time constant is of the order of the decay constant of the phosphor, a lower pulse will be observed than if the R C time constant is comparatively longer. This is due to the fact that the charge leaks off the capacitor just as quickly as it is fed on.

It was found that, with the particular circuit used, it was necessary to have a pulse length of the order of 1 μ seconds before the pulse was large enough to activate the coincidence circuit. This is long compared with the decay constant of the terphenyl crystal (0.012 μ sec.), and is the principal factor in determining the resolving time of the complete counter.

4. Tests

(a) Coincidence Circuit

A Hewlett-Packard pulse generator was available with which to test the circuit. The generator produced a square pulse of adjustable voltage, positive or negative, and variable in length from 10 to 0.2 u sec. It was also provided with a synchronizing pulse, about 37 volts of either sign and 2 u sec in length, with an adjustable delay line so that the signal pulse could be delayed up to 100 u sec after the synchronizing pulse.

F or the first test, the signal pulse was applied to both grids of the 6SA7 coincidence tube. With a pulse of -20 volts on each grid, the coincidence circuit output gave a positive pulse of 4.5 volts, and with a maximum input of -55 volts a +17-volt pulse was produced. Between these two points, the output varied approximately linearly with the input.

For the second test, the signal pulse was placed on one grid, and the synchronizing pulse on the other. When no delay was imposed, and the signal pulse set at -11 volts, the coincidence pulse was +3.2 volts. When the signal was delayed so that no coincidence occured, both input pulses fed through to give output pulses of +1.5 volts. This made it possible to observe on the oscilloscope the actual delay of the signal pulse. An output pulse of +11 volts was observed when the signal pulse was raised to -31 volts. Again the output varied linearly between these two points.

Finally, the delayed pulse was moved slowly ahead until it began to overlap the synchronizing pulse. A coincidence pulse was observed when the two input pulses overlapped by about 0.2 u secs. The output pulse was approximately the same length as the overlap of the two input pulses.

The generator pulses had quite sharp edges, whereas the pulses from the scintillation counter had sloping edges and a steep maximum. The coincidence pulse therefore reached its full voltage only if the coincidence was very close. This is a definite advantage because pulses due to incident radiation were usually in exact coincidence. Accidental coincidences, causing only a partial overlap, gave output voltages of lower voltage. Those less than 3 volts were eliminated by the discriminator.

(b) <u>Relation of Accidental Coincidences to Temperature of Multipliers</u>

Since temperatures as high as 60°C may be encountered in a deep borehole, a test was made to determine the effect of temperature on the accidental noise coincidences. The photomultipliers were immersed in a controlled temperature water bath, and held at various temperatures while the background counts were taken. The results of the test are plotted in Figure 9 which shows the expected rapid increase of background with increasing temperature.

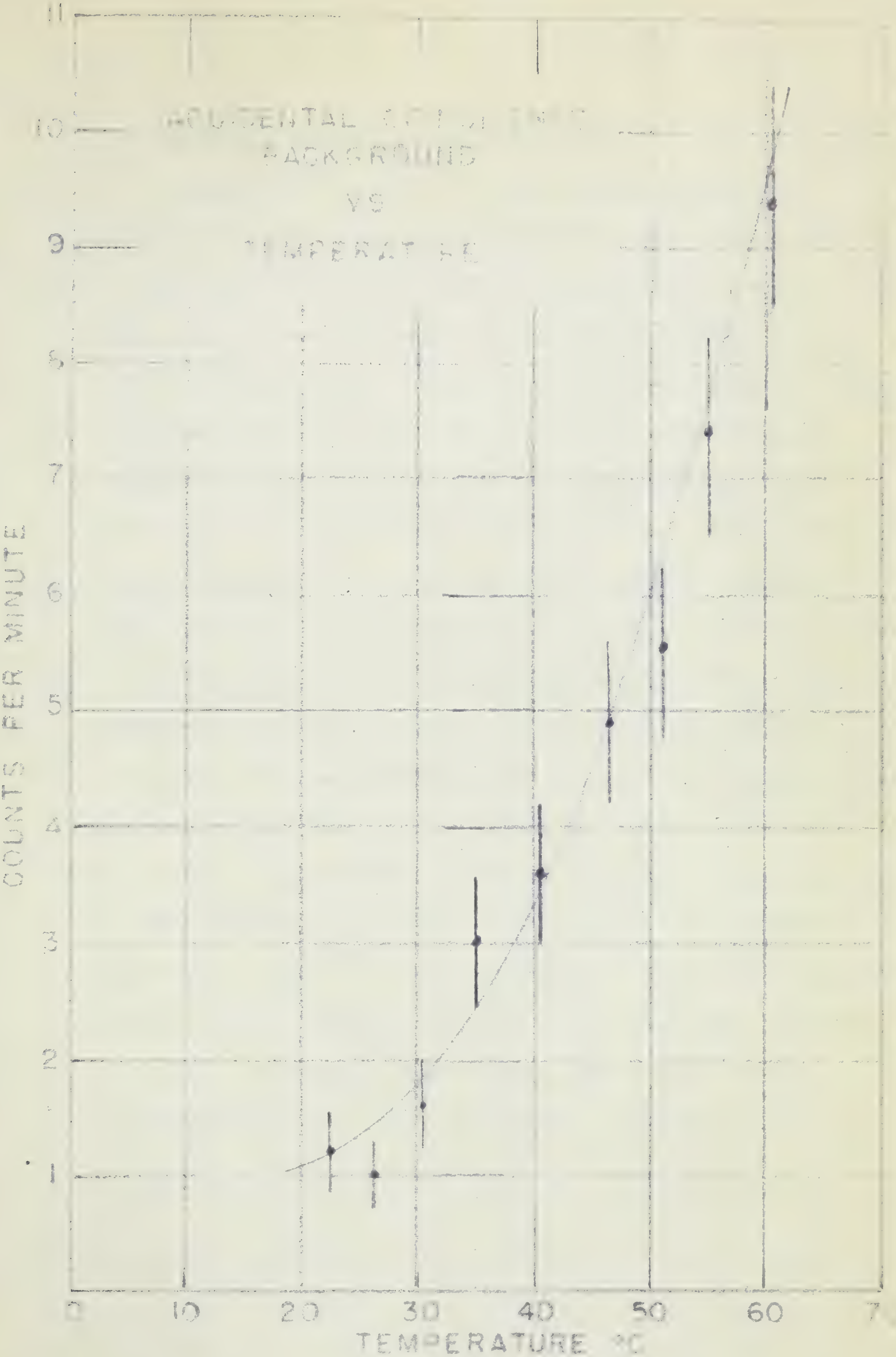
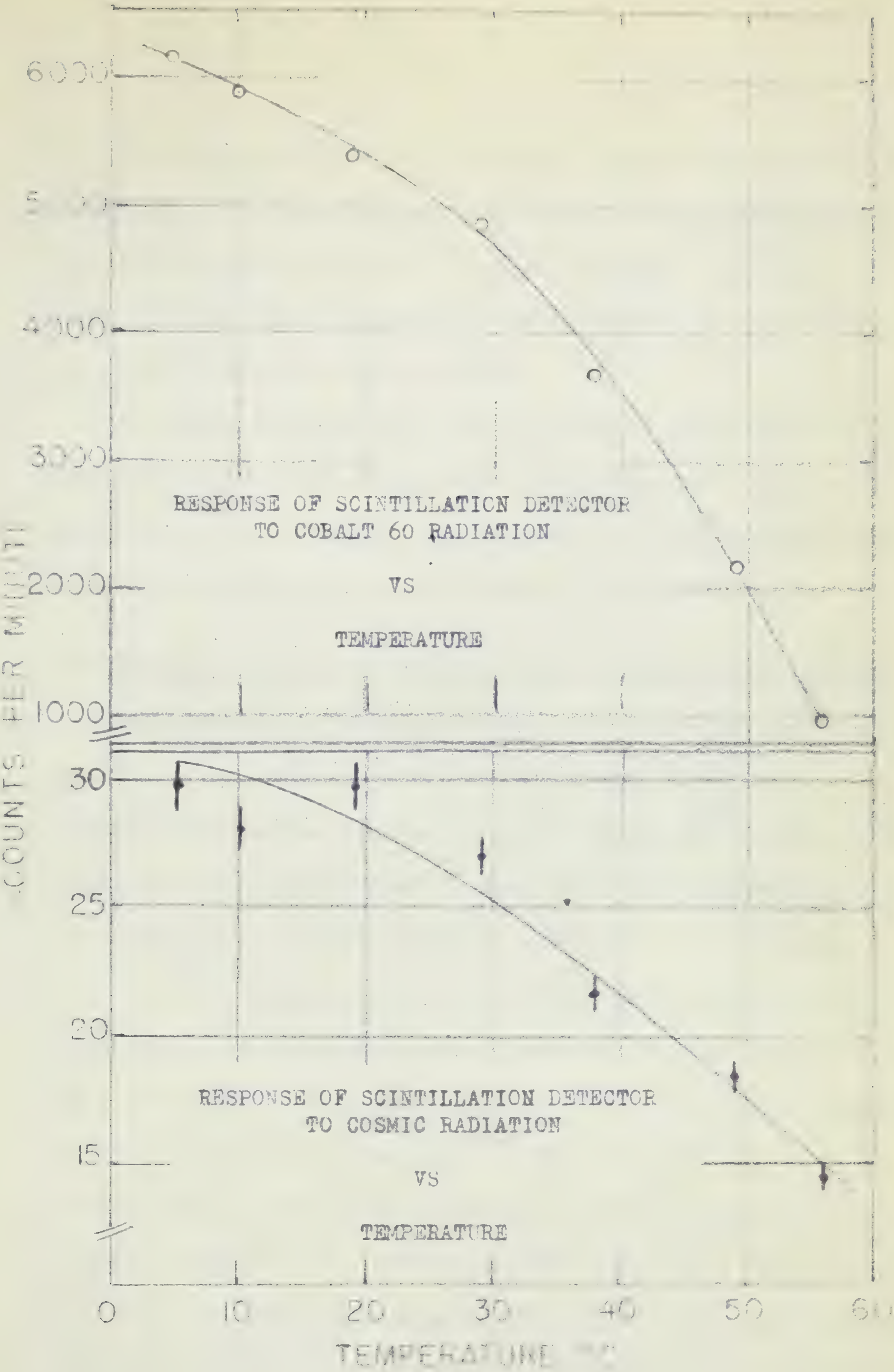

BACKGROUND
VS
COUNTS PER MINUTE
TEMPERATURE °C
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
9
10
11

Figure 9.

(c) Affect of Temperature Upon Signal Count

It was necessary, also, to test whether the gamma-ray sensitivity of the completed counter varied with temperature. For this purpose the whole instrument, including the outer casing, was placed in a barrel of water which could be filled with hot or cold water. On account of the large volume of water the temperature did not vary by more than a degree during the time necessary to make a reading, and no special temperature control was necessary. Counts were made of the natural coincidences due to cosmic radiation, and also with a cobalt 60 source at a fixed distance. Figure 10 shows the response of the detector to to these two radiations at various temperatures. The probable errors for the cobalt 60 counts are not shown, since they are negligible on the scale of the graph at these high counting rates. The response was found to drop off at the higher temperatures, apparently in contradiction to the results obtained from test (b). The only explanation is that the terphenyl crystal is sensitive to temperature. There ~~is~~ are no data available to support this statement, although similar effects have been observed with other crystals (14) (15). According to Engstrom (16) the response of the photomultiplier tubes increases slightly, although not in proportion to the background noise.



RESPONSE OF SCINTILLATION DETECTOR TO COBALT 60 RADIATION
VS
TEMPERATURE
RESPONSE OF SCINTILLATION DETECTOR TO COSMIC RADIATION
VS
TEMPERATURE
6000
4000
3000
2000
1000
30
25
20
15
0
10
20
30
40
50

Figure 10.

When the response curve for cosmic rays is corrected for the accidental coincidence background (which becomes appreciable at the higher temperatures) the response decreases by a factor of about 1/6 over the temperature range concerned, in agreement with the result for the cobalt 60 source.

It should be noted that the temperatures shown in Figure 10 are those of the water surrounding the instrument. The actual temperature inside the case was probably somewhat higher on account of the heat generated by the filaments of the vacuum tubes.

(d) Effect of Time of Operation of the Instrument Upon Response

The stability of the instrument is of importance, so a study was made of the response after the instrument had been in operation for various lengths of time. Figure 11 is a plot of the cobalt 60 count against time of operation. The response dropped off quickly for the first hour and a half and then flattened out. This can be attributed to a fatigue effect on the photo-multipliers. Engstrom (16) states that the fatigue will disappear after the tube has been allowed to rest for a few hours. Even on the flat part of the curve, some of the points deviate from the straight line by much more than the statistical probable error of the high counting rate. Jordan and Bell (17) state that a broadening of the classical Poissonian distribution of the incident gamma rays may be caused by a statistical distribution of the secondary emission in the dynode stages. Either this factor, or instability of the instrument, could account for the fluctuations observed.

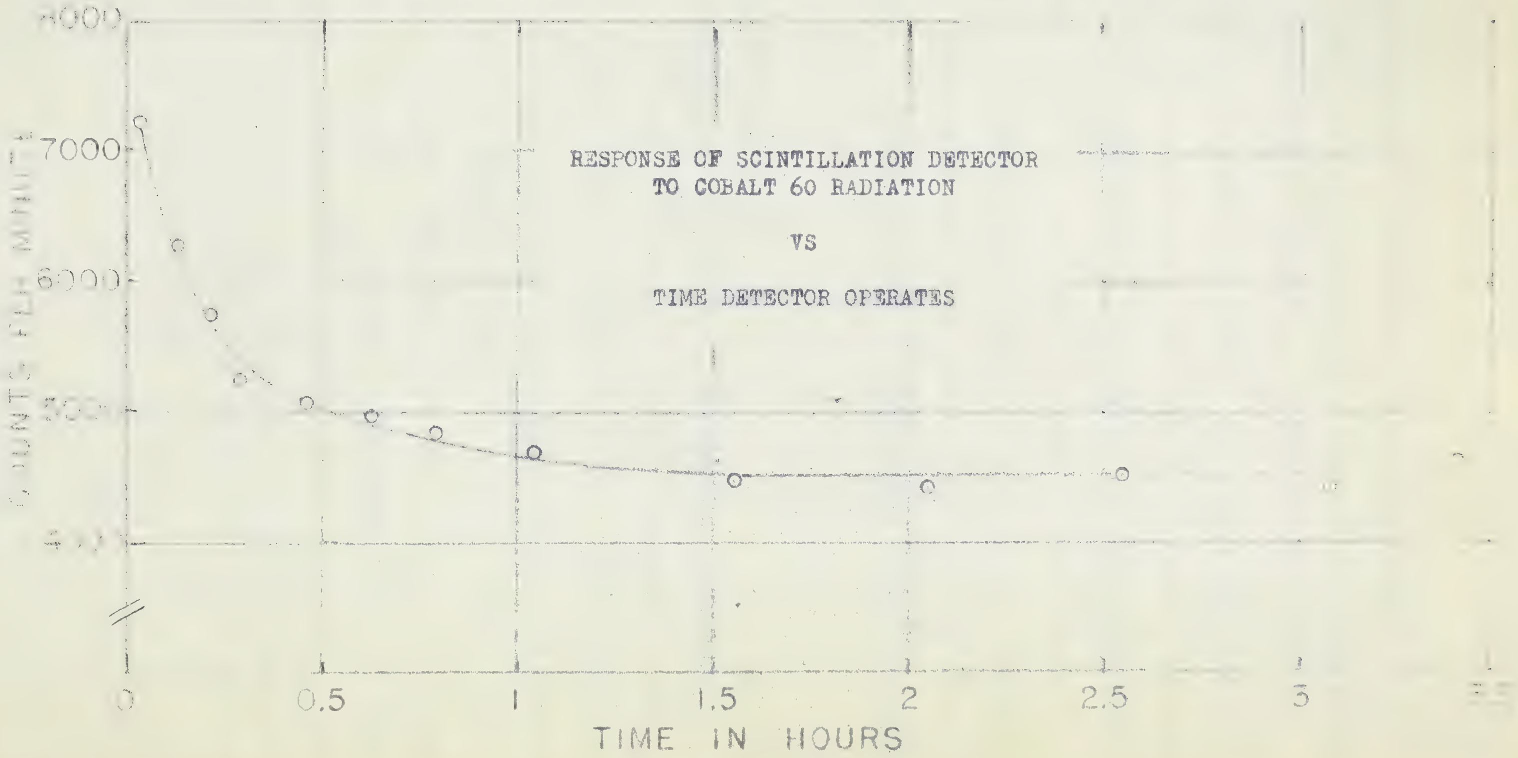

RESPONSE OF SCINTILLATION DETECTOR
TO COBALT 60 RADIATION
VS
TIME DETECTOR OPERATES
7000
6000
0
0.5
1
1.5
2
2.5
3
TIME IN HOURS

Figure 11.

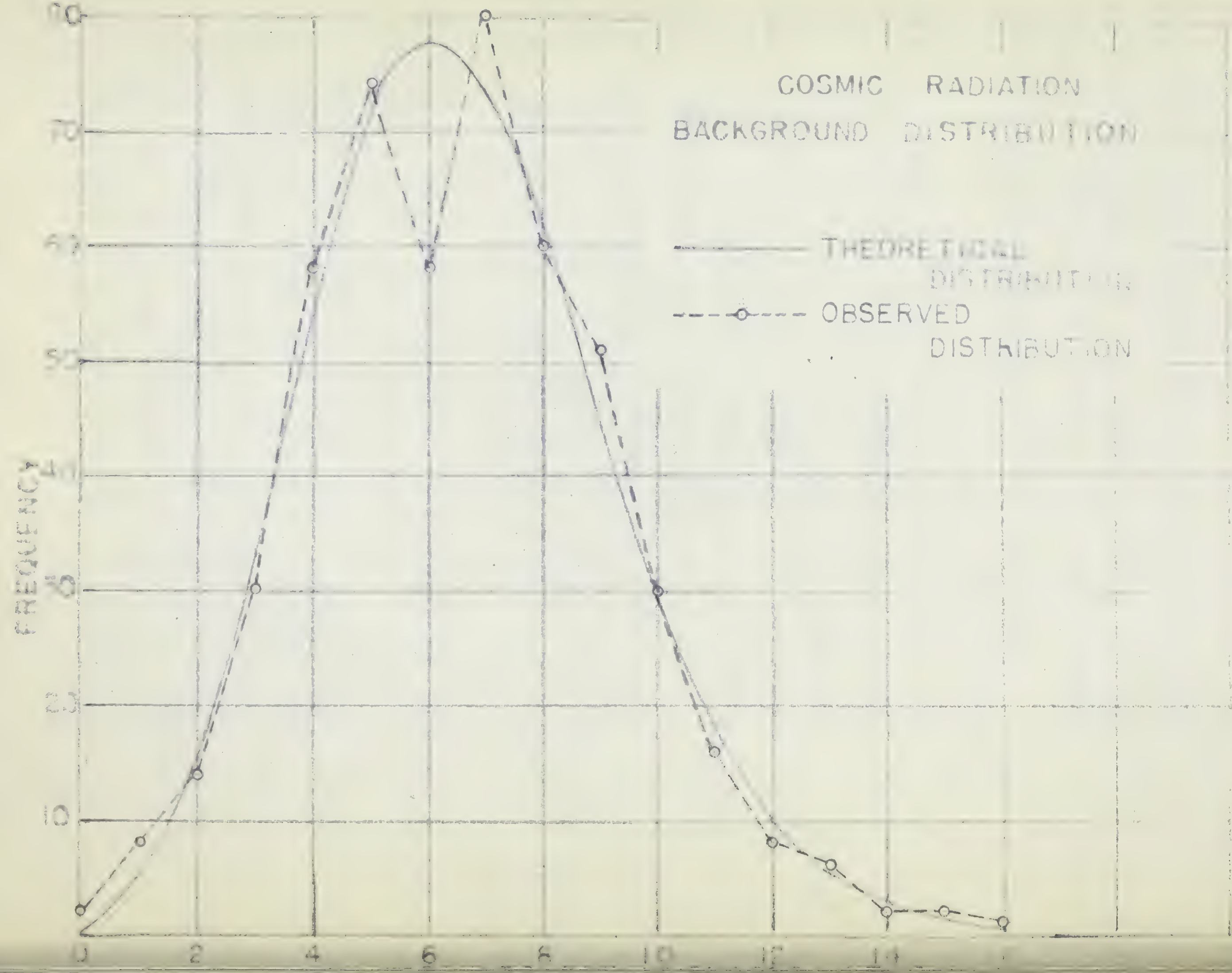
(e) Statistical Distribution of the Cosmic Background

To check the time distribution of the counts obtained, 500 readings of 8 second intervals were taken for the cosmic-ray background. By applying the standard Chi Square test for curve fitting it was determined that there was a 30% probability that the observed distribution was Poissonian. If this probability is as high as 10% one can treat the observed distribution as the same as the theoretical distribution in deriving probable errors. Such is the case here, so the Poisson distribution can be assumed. Both the observed and theoretical distributions are plotted in Figure 12.

(f) Efficiency of Counter

To estimate the efficiency of the counter, a Radioactive Products, Inc.* roentgen meter was used to determine the flux of gamma radiation from the cobalt 60 source. Cobalt emits two gamma rays, of 1.1 and 1.3 Mev energy. To simplify the calculations a single average energy of 1.2 Mev. was assumed. For 1.2-Mev. gamma rays the linear absorption coefficient in air is 3.5×10^{-5} cm^{-1}. A roentgen is defined as that quantity of gamma radiation which will produce 2.083×10^{9} ion pairs per cc of standard air, which represents an absorption of energy of 6.77×10^{4} Mev per cc of

*Model D-1 Radiation Survey Meter.


COSMIC RADIATION
BACKGROUND DISTRIBUTION
THEORETICAL DISTRIBUTION
OBSERVED DISTRIBUTION
FREQUENCY
70
60
50
40
30
10
0
2
4
6
8
10
12
14

standard air. Using these figures it is possible to determine that a flux of 2.69×10^4 quanta per cm^2 per minute of 1.2 Mev gammas is required to produce 1 milli roentgen per hour. With the geometry used, an intensity of 2.0 ± 0.4 mr/hr was observed at the location of the scintillation counter. The large possible error is due to the limitations of the roentgen meter. The area presented by the crystal was 6 cm^2, so that the total number of gamma rays which were incident upon the crystal per minute was

$$2 \text{ mr} \times 6 \text{ cm}^2 \times \frac{2.69 \times 10^4 \ \frac{\text{quanta}}{\text{cm}^2\ \text{min}}}{\frac{\text{mr}}{\text{hr}}} = (3.2 \pm 0.6) \times 10^5 \ \frac{\text{quanta}}{\text{min}}$$

This figure is to be compared with the observed counting rates.

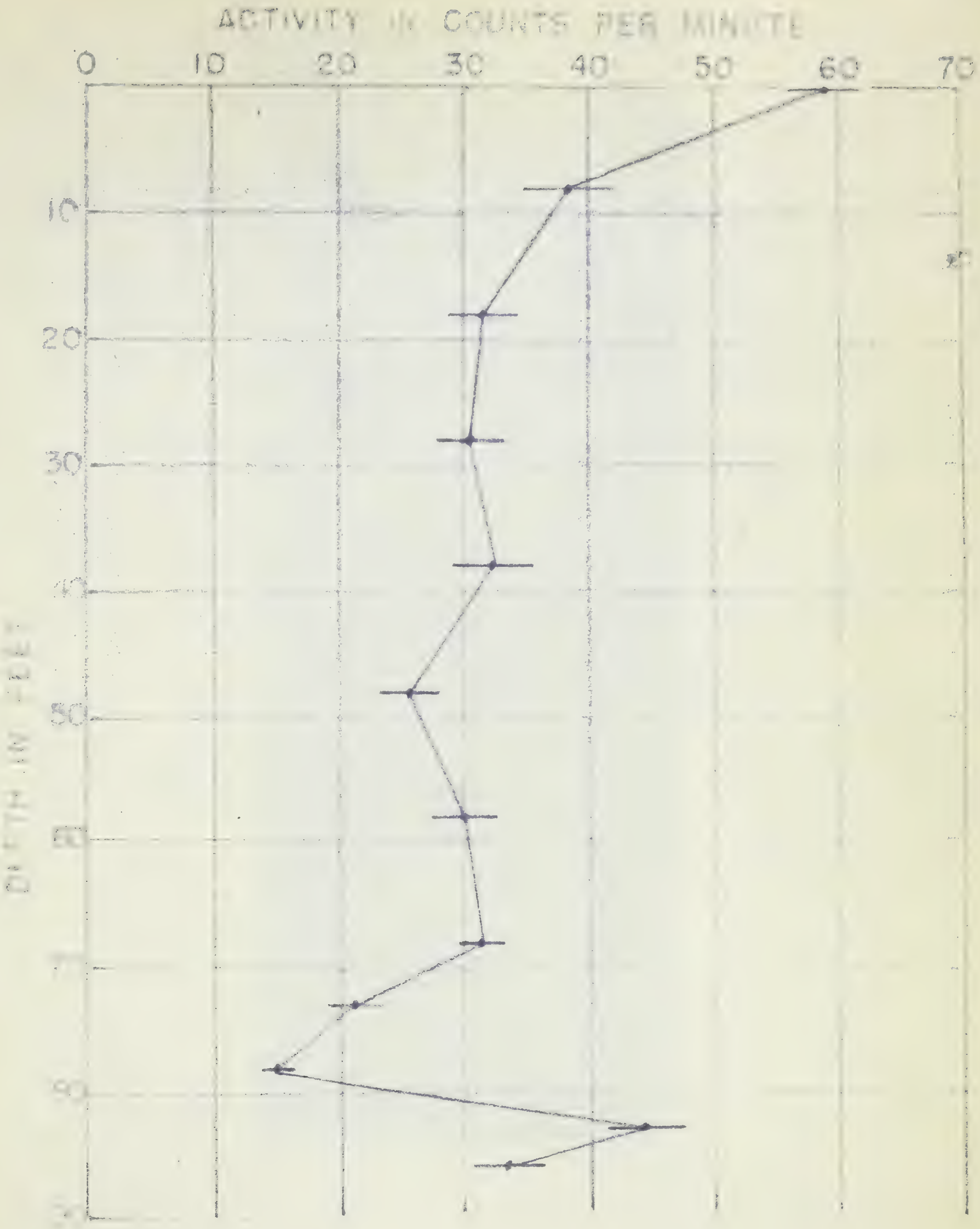
For the crystal alone, with no case or covering, other than a dark cloth, the observed rate was 26,300 cp.m., giving an efficiency of 8.2%. For the same as above except for a tinfoil reflecting coat on the crystal the rate was 31,200 cp.m., an efficiency of 9.7%. With the tinfoil, the photomultiplier can, and the instrument in its aluminum case the rate was 21,200 cpm, an efficiency of 6.6%.

These efficiencies are low compared to those claimed by various authors, most of whom give an efficiency of about 20% for gamma rays, while a few go as high as 30% when using elaborate reflecting mirrors to direct all light produced to the photocathode.

However, these high efficiencies are in the case of one tube only. Using the coincidence method, the light produced by one gamma ray quantum must be divided between both tubes. Since a certain amount of light will be absorbed by the crystal during transmission, it is quite reasonable that the efficiency for such an instrument would be lower than the efficiency of a single tube instrument.

(g) Log of Water Well

Figure 13 shows the gamma ray log of a water well on the property of the Lane Wells Company at Edmonton, Alberta, obtained with the scintillation type detector. When it was found that the counting rate was not high enough to allow logging the well by moving the instrument at a constant rate, the recorder was disconnected, and 4 one minute readings were taken on the scaler every 10 feet. A definite low was observed at the 78 foot level, so the recorder was reconnected, and readings approximately 5 minutes long were taken at 68, 73, 78, and 83 feet. The Lane Wells Company had taken, about two years previously, a gamma-ray log of the well by their ionization method, which is shown in Figure 14. The agreement between the two is fairly close, especially in the 75 to 82 foot interval. The personnel of the Lane Wells Company interpreted the low at 78 feet to be due to a seam of coal.



GAMMA RAY LOG OF WATER WELL
WITH SCINTILLATION DETECTOR

Figure 13.

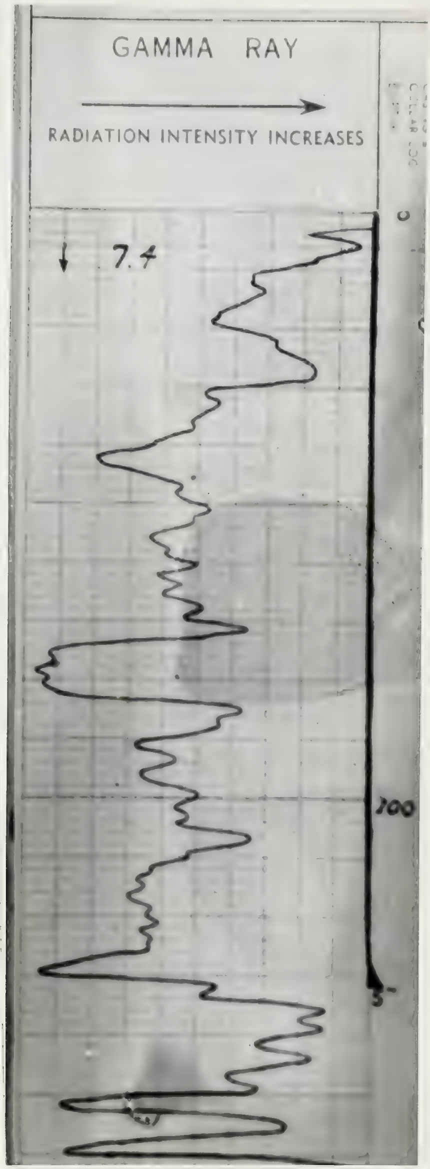


Figure 14. Lane-Wells' Gamma-Ray
Log of Water Well

The Lane Wells Company took their log of the well at 30 feet per minute, whereas with the scintillation detector, it took a time of about 1 hr. of actual readings to obtain the sketchy results shown in Figure 11. This proves that the scintillation detector, as it is now, is not sensitive enough to permit the logging of wells economically. If it could be improved by a factor of 5 or so, it would probably prove practical.

The detector and its associated equipment in the field are shown in Figure 15.

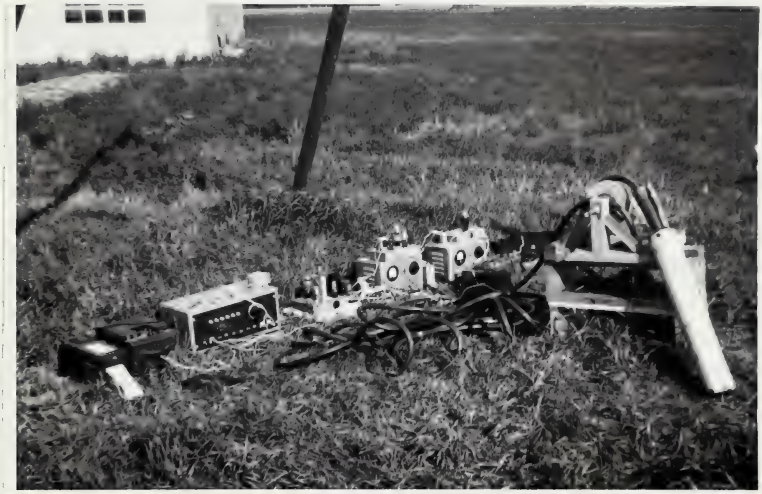


Figure 15. Apparatus in Field

5. Discussion

(a) Conclusions

It may be concluded from the above results, that the scintillation counter as constructed for these trials, is not a practical instrument for gamma-ray well loggings. Firstly, it is not sensitive enough to permit logging at an economical speed, and still retain the necessary accuracy. Secondly, the manner in which the response drops off at high temperatures would seriously impair a log in a deep well, unless compensation was made for the temperature changes. Even with a correction for temperature, it would be necessary to decrease the speed of logging at high temperatures.

(b) Recommendations

Improvements are required in both the sensitivity, and the temperature dependence of the instrument. To improve the sensitivity, a more sensitive type of photomultiplier could be used. The more sensitive tubes have a low noise background, so that the tube could be operated at a higher voltage to provide a higher gain. If a higher gain was obtained, it would be possible to shorten the pulse length. (See Section 3 (d)). This would reduce the number of accidental coincidences and not effect the signal count. Another plan to increase the sensitivity would be to use a crystal, such as NaI which has a higher efficiency for gamma rays.

As seen from Table I, the 9314 type of photomultiplier has a small photocathode compared to the 5819 end window tube. If 5819 tubes were used, a much larger phosphor would be practical.

Temperature control is the major problem. Mr. Benjamen of the Lane-Wells Company at Edmonton has said that at present Lane-Wells has about four scintillation detectors in the field in the U. S. A. They are trying to keep the tubes and crystal at a constant low temperature with liquid air, or dry ice. This, however, is proving very difficult, since a tremendous pressure is built up inside the instrument as these materials vaporize. However, something of this nature must be done in order to obtain reliable results at a constant logging speed.

It is probable that a scintillation counter suitable for radioactive well logging could be developed. However, it is certain that it would require a great deal more research, besides equipment which is not now available, and might be difficult to obtain.

Acknowledgements

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The cooperation of the Lane-Wells Company in providing a well for field tests is appreciated.

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